Acoustic Beamforming with Digital Hearing Aids

Qualifier Exam

Olivier Roy

LCAV - I&C - EPFL

Joint work with Martin Vetterli

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Outline

1. Motivations
2. The Rate-Constrained Hearing Aid Problem
3. Remote Source Coding with Side Information
4. Gain-Rate Analysis
5. Conclusions
6. Future Directions of Research

Motivations (1/4)

Generalities

- Battery-operated sensing devices
- Types: behind-the-ear (BTE), in-the-ear (ITE), in-the-canal (ITC) and completely-in-the-canal (CTC)

- Analog vs. digital
- 1 to 3 (omni-)directional microphones, 1 loudspeaker

Motivations (2/4)

Goals

- Overcome user's hearing impairment
- Noise reduction
- Improve speech intelligibility
- ...

Motivations (3/4)

How to achieve theses goals?

- Spectral shaping
- Beamforming

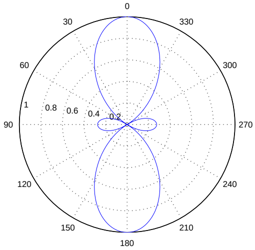


Figure: Example of beampattern at $f = 1000$ [Hz] for 2 microphones separated by d=0.2 [m].

Motivations (4/4)

- Assistive listening devices

(a) (b)

Figure: Assistive listening devices. (a) Remote microphone. (b) Collaborating hearing aids.

- Assistive listening devices

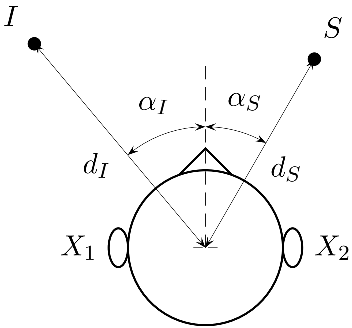
(a) (b)

Figure: Assistive listening devices. (a) Remote microphone. (b) Collaborating hearing aids.

$\boxed{\text{Fundamental gain-rate tradeoff}}$

The Rate-Constrained Hearing Aid Problem (1/5)

- Head-related configuration:



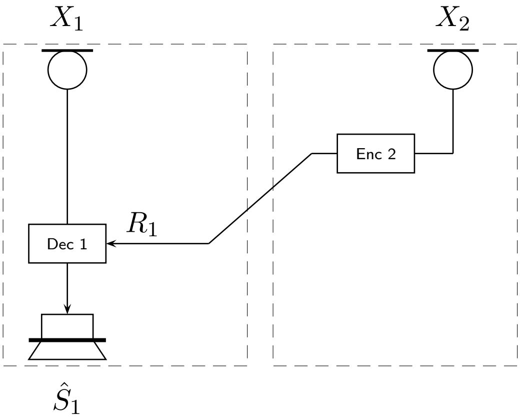
- Signal recorded at hearing aid l ($l = 1, 2$) given by

$$
\begin{aligned}
X_l(t) &= S_l(t) + I_l(t) + N_l(t) \\
&= [h_l * S](t) + [g_l * I](t) + N_l(t)
\end{aligned}
$$

The Rate-Constrained Hearing Aid Problem (2/5)

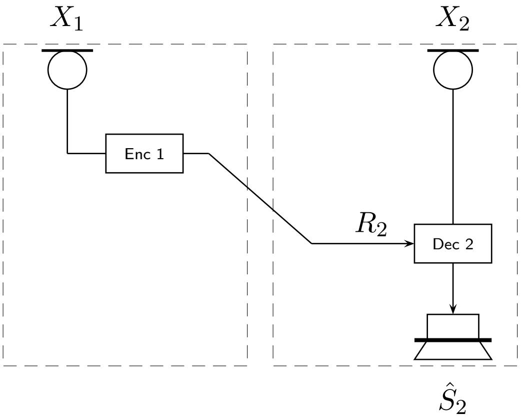
Local perspective

- Setup:



Local perspective

- Setup:



The Rate-Constrained Hearing Aid Problem (3/5)

Local perspective

- Weighted mean-squared error (MSE) criterion:

$$D_1 = \mathrm{E}[\|A(S_1 - \hat{S}_1)\|^2]$$

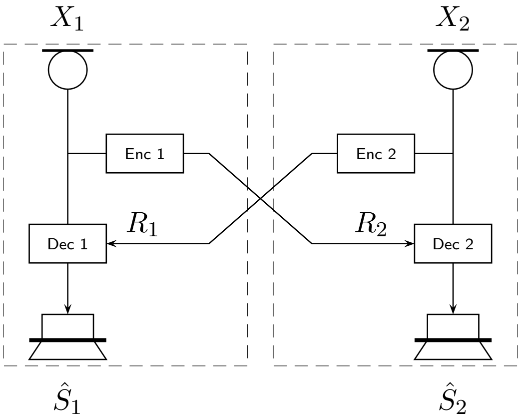
- Remote source coding problem with side information at the decoder
- We define the local gain-rate function at hearing aid 1 as

$$G_1(R_1) \stackrel{def}{=} \frac{D_1(0)}{D_1(R_1)}$$

The Rate-Constrained Hearing Aid Problem (4/5)

Global perspective

- Setup:



The Rate-Constrained Hearing Aid Problem (5/5)

Global perspective

- Weighted MSE criterion:

$$D = \mathrm{E}[\|A(S_1 - \hat{S}_1)\|^2] + \mathrm{E}[\|A(S_2 - \hat{S}_2)\|^2]$$

- Two separate remote source coding problems with side information at the decoder
- We define the global gain-rate function as

$$G(R) \stackrel{def}{=} \frac{D(0)}{D(R)}$$

where $R = R_1 + R_2$

Remote Source Coding with Side Information (1/3)

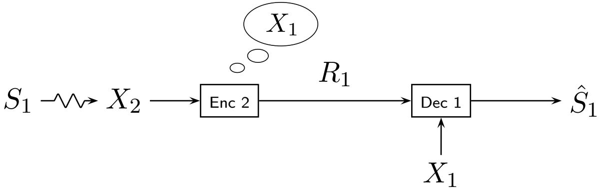
Two classes of coding strategies

- Side-information-aware (SIA) coding: the SI available at the decoder is taken into account at the encoder
- Side-information-unaware (SIU) coding: the SI available at the decoder is neglected at the encoder

Remote Source Coding with Side Information (2/3)

SIA coding

- Setup:



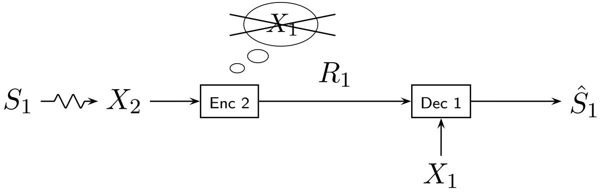
- Motivation: optimal in a RD sense
- The coding intuition:

  "Get the best estimate of S_1 based on the part of X_2 that the decoder cannot predict with X_1 and then encode this estimate"

Remote Source Coding with Side Information (3/3)

SIU coding

- Setup:



- Motivation: suboptimal but simpler
- The coding intuition:

  "Get the best estimate of S_1 based on X_2 and then encode this estimate"

Gain-Rate Analysis (1/7)

Local perspective

- Simple scenario: gain-rate functions

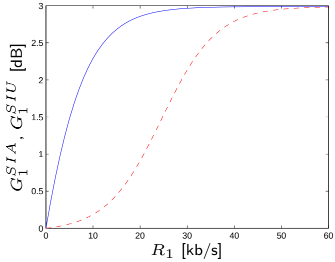


Figure: Typical gain-rate function with SIA coding (plain) and SIU coding (dashed).

Local perspective

- Simple scenario: gain-rate functions

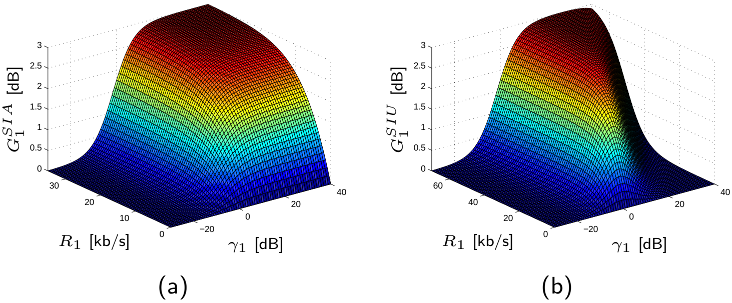
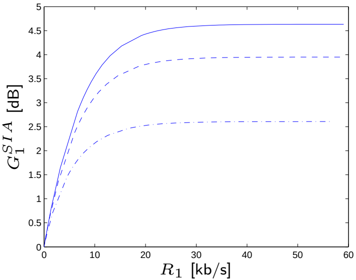


Figure: Typical gain-rate functions. (a) SIA coding. (b) SIU coding.

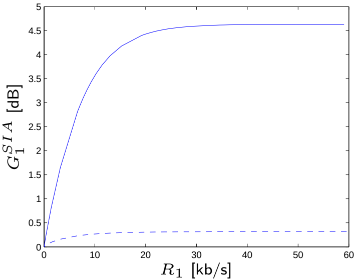
Gain-Rate Analysis (3/7)

Local perspective

- General scenario: gain-rate functions



(a)



(b)

Figure: Gain-rate functions with SIA coding. (a) $\alpha_I = 5, 8, 10$ [deg] (bottom to top). (b) $d = 0.2$ [m] (plain) and $d = 0.02$ [m] (dashed).

Gain-Rate Analysis (4/7)

Local perspective

- General scenario: optimal rate allocation across frequencies

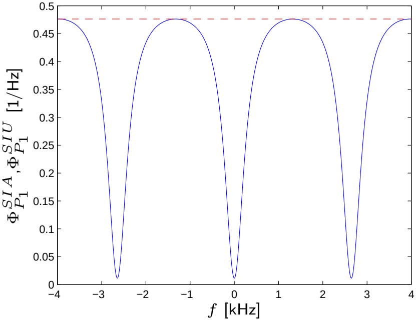
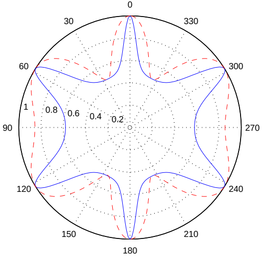


Figure: Reverse "water-filling" power spectral density with SIA coding (plain) and SIU coding (dashed).

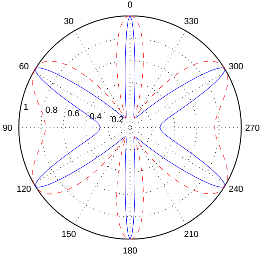
Gain-Rate Analysis (5/7)

Local perspective

- General scenario: rate-constrained directivity patterns (RCDP)



(a)



(b)

Figure: Typical RCDP with SIA coding (plain) and SIU coding (dashed) at $f = 2000$ [Hz] with $d = 0.2$ [m]. (a) $R_1 = 0.1$ [b/s/Hz] and (b) $R_1 = 1$ [b/s/Hz].

Gain-Rate Analysis (6/7)

Global Perspective

- Simple scenario: optimal rate allocation between the hearing devices

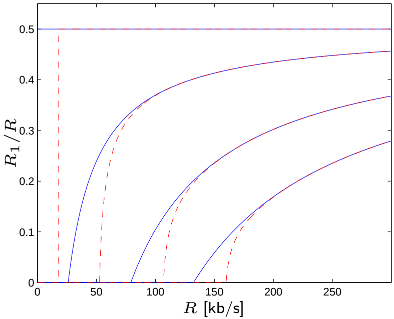


Figure: Rate allocation benefitting to hearing aid 1 with SIA coding (plain) and with SIU coding (dashed) for different SNRs.

Gain-Rate Analysis (7/7)

Global Perspective

- General scenario: similar to local perspective

Also ...

- Head-shadow effect
- Perceptual weighting operator
- PSDs from speech excerpts

Conclusions

To conclude

- Identification of the problem
- Local & global perspectives
- Gain-rate characterization for SIA and SIU coding
- Optimal rate allocation policies
- Numerical results

Future Directions of Research

What's next? Beamforming with few microphones

- Acoustic scene is sparse (time-frequency)
  - Rarely the worst-case scenario
  - "Sparse nulling"
  - Perceptually motivated optimization
- Sources are very well located in space
  - Shannon's sampling theorem not suited
  - Parametric representations (e.g. finite rate of innovation)